UltraShiver: Lateral Force Feedback on a Bare Fingertip via Ultrasonic Oscillation and Electroadhesion

Heng Xu, Michael A. Peshkin, and J. Edward Colgate

Abstract— **We propose a new lateral force feedback device, the UltraShiver, which employs a combination of in-plane ultrasonic oscillation (around 30 kHz) and out-of-plane electroadhesion. It can achieve a strong active lateral force (400 mN) on the bare fingertip while operating silently. The lateral force is a function of pressing force, lateral vibration velocity, and electroadhesive voltage, as well as the relative phase between the velocity and voltage. In this paper, we perform experiments to investigate characteristics of the UltraShiver and their influence on lateral force.**

I. Introduction

Among haptic rendering technologies, lateral forces between the human fingertip and an object's surface play an important role in creating the illusion of texture and shape perception [1]–[7]. By modulating the lateral friction force, spatial friction maps of physical textures can be generated [1]–[4] and the profile gradient of a 2.5D shape can be approximately matched [5]–[7].

To modulate the friction force, there are two methods, including ultrasonic friction reduction (what we call the TPaD) [1], [8] and electroadhesive attraction [2], [3], [9]. Ultrasonic friction reduction uses the squeeze film effect to create a lubricating layer of over-pressurized air between a fingertip and a vibrating surface, thus decreasing friction. The electroadhesive attraction method is based on a display surface in which an electrode layer is placed on top of a substrate and covered by an insulating layer. When the grounded fingertip touches the insulating layer, there is an electric field generated across the skin-surface interface. The electric field creates coulombic attraction and increases friction forces.

However, since the friction force is a passive lateral force and only resists the finger motion, it cannot assist in perception of shapes that would cause forces perpendicular to or in the same direction of movement [7]. That makes active lateral force feedback essential for virtual shape rendering.

Many interesting devices have been developed to generate active lateral force feedback on the fingertip, [10]–[16]. Many of these use electric motors and articulated mechanical components to deliver the in-plane forces, which makes them difficult to apply to touchscreens where the expectation is no moving parts [10]–[12]. Motivated by the goal of achieving active lateral force feedback in a "solid state" device, our group has studied lateral force feedback displays for ten years and we have developed a range of devices, including the ShiverPaD, the LateralPaD, and the eShiver [13], [14], [16].

The ShiverPaD consisted of a TPaD, a voice coil, and auxiliary structures [14]. The voice coil was used to oscillate the TPaD laterally. Over the course of part of an oscillation cycle, the friction was set low, and over the remainder of the cycle it was set high. This asymmetry enabled the ShiverPaD to generate a net lateral force in each cycle. One prototype was able to achieve around $\pm 100mN$ lateral force at a vibratory frequency of 854 Hz.

The eShiver used a similar apparatus to provide the in-plane motion [16]; however, it used electroadhesion ([9], [17]) to modulate the friction force. The eShiver performed at a relatively low frequency of 55 Hz for an artificial finger and 1000 Hz for the human finger. It could generate a maximum lateral force of $\pm 450mN$ on a human finger, making it more than strong enough for any envisioned use.

Even though the ShiverPaD and the eShiver were relatively reliable and able to generate adequate force feedback, their actuators were large and their operating frequencies were audible, which poses a serious limitation.

To generate lateral force in the ultrasonic regime, the LateralPaD, built in 2012, used piezoelectric actuators to drive normal and lateral resonances at the same ultrasonic frequency (22.3 KHz) [13]. Unlike the principle of the ShiverPaD and the eShiver, the LateralPaD used a circular motion of the surface, similar to a traveling wave ultrasonic motor [18], to generate the lateral force. The LateralPaD could generate $\pm 50mN$, a force small enough that approximately 20% of people could not feel it during a demo session [19].

In this paper, we describe a new a haptic device, the UltraShiver, that can provide large lateral forces while operating in the ultrasonic regime (around 30 kHz). It oscillates an electroadhesive surface in-plane by using an ultrasonic longitudinal wave. The direction and magnitude of the lateral force can be adjusted by varying the phase between the in-plane oscillation and the electroadhesion. The UltraShiver makes it possible, for the first time, to apply large active lateral forces to a human fingertip in a solid state device, without audible artifact.

II. Prototype Design and Analysis

A. UltraShiver Structure

The UltraShiver consists of a sheet of anodized aluminum excited in a compression-extension mode via piezoelectric actuators (Figure 1). The anodized aluminum serves as an electroadhesive surface in which the aluminum layer is

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connected to a high voltage source and the anodized layer is an insulator.

The dimensions of the anodized aluminum are 84mm x 60mm x 1mm. Two pieces of hard piezoceramic (SMPL60W5T03R112, Steminc and Martins Inc, Miami, FL, USA) are placed in the middle of the anodized aluminum. The two piezoelectric actuators are excited symmetrically, which exaggerates the oscillation in the in-plane direction and reduces the oscillation in the out-of-plane direction. We optimized the geometry of the UltraShiver design to make the resonant frequency of the lateral oscillation far away from the resonant frequency of the normal oscillation, thus further decreasing the normal motion.

B. Finite Element Analysis

We simulated the motion of the UltraShiver using ABAQUS (ABAQUS Inc), which showed an extension-compression mode at the longitudinal resonance (in figure 2). There is only one nodal line in the middle of the anodized aluminum, which is parallel to the short edge of the anodized aluminum. Due to the symmetric motion of the two sides, we need to analyze the performance on only the left or right side of the piezoelectric actuator.

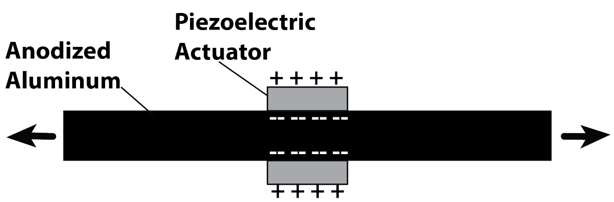


Fig. 1. Side view of the UltraShiver.

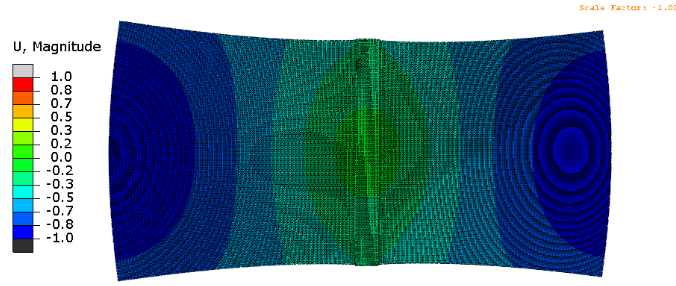
C. Velocity Profile Measurement

Since the oscillation of the surface is one of two fundamental features in the UltraShiver, it is necessary to characterize the velocity profile of the entire surface, including both lateral and normal components.

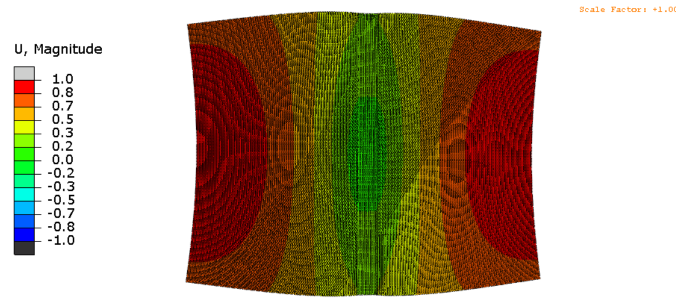
We measured the velocity at 14 points, all on the left side of the piezoelectric actuator (see Fig. 3). These points ran parallel to the long side of the surface 20 mm from the edge, and were spaced 2.5 mm apart. The normal velocity was measured using a Laser Doppler Vibrometer (LDV). The lateral velocity was measured using a custom electromagnetic induction sensor. The UltraShiver was placed in a uniform magnetic field of 0.38 Tesla and a 5 mm long magnet wire was glued to each point, parallel to the short edge of the surface and perpendicular to the direction of the magnetic field. Lateral movement of the UltraShiver induced a voltage in each magnet wire. This voltage was amplified and then recorded by an NI USB-6361. Each measurement was repeated five times.

III. Lateral Force Generation

The lateral force generation depends on the in-plane ultrasonic oscillation and the out-of-plane electroadhesive force, both operating at 30.1 kHz. The in-plane oscillation of the UltraShiver generates a lateral reaction force ($F_l = Z_l * v_l$) on the fingertip, which is related to the fingertip's mechanical impedance in shear (Z_l) and its lateral velocity (v_l). The out-of-plane electroadhesive force ($F_e \propto {V_{gap}}^2$) adjusts the friction force between the fingertip and the surface, and depends on the gap voltage (V_{gap}) between the fingertip and surface [9], [17].



(a) Peak extension



(b) Peak compression

Fig. 2. Finite element analysis of the UltraShiver.

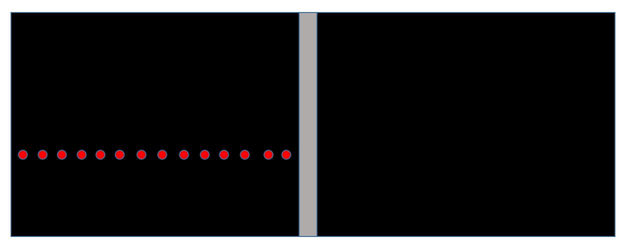


Fig. 3. Measurement points of the velocity profile. The black block represents the anodized aluminum. The gray block represents the piezoelectric actuator. The red dots represent points where velocity was measured.

As illustrated in figure 4, the UltraShiver's operation can be divided into two phases within one period of in-plane vibration: a "push phase" and a "slide phase". In the "push phase", the gap voltage is set to a high value, compared to the "slide phase". The friction force (F_{push}) in the "push phase" is higher than that (F_{slide}) in the "slide phase", leading to a net pushing force.

There is a range of lateral velocities (v_l) for which the lateral reaction force (F_l) is less than F_{push} and larger than the low friction force (F_{slide}) in the "slide phase". In this condition, the fingertip will slide in the "slide phase" and be stuck in the "push phase". The theoretical maximum net lateral force (F_{net}) is equal to

$$F_{net} = \frac{F_l - F_{slide}}{2} = \frac{Z_l * v_l - F_{slide}}{2} \quad (1)$$

In this case, the net lateral force is sensitive to the relative lateral velocity (v_l) and the gap voltage in the "slide phase".

When the lateral velocity (v_l) is even higher, the lateral reaction force (F_l) can be larger than F_{push}. The fingertip then slides in both phases. In this case, the theoretical maximum net lateral force (F_{net}) is equal to

$$F_{net} = \frac{F_{push} - F_{slide}}{2} \quad (2)$$

In this situation, the net lateral force is sensitive to the gap voltage in the two phases.

When the relative lateral velocity (v_l) is very low, the lateral reaction force (F_l) can be less than F_{slide}. Then the fingertip is stuck in both phases, and the net lateral force (F_{net}) is equal to zero.

Thus, the UltraShiver can control the amplitude of the net lateral force by adjusting the amplitudes of the lateral velocity and the gap voltage. In addition, it can also change the direction of the net lateral force by adjusting the phase between the lateral velocity and the gap voltage.

In the UltraShiver, the voltage of piezoelectric actuators is used to control the lateral velocity of the surface. Even though the gap voltage (V_{gap}) is related to the electroadhesive force, it cannot be controlled directly. Instead, we control the total voltage (V_{total}) of the system (across the fingertip, the plate, and the air gap between them). Together with an electrical impedance measurement and an electrical model of the UltraShiver, we can estimate the voltage across the air gap. A detailed description of the electrical impedance model used in this study can be found in [9]. In addition, we assume that the total impedance of the system (Z_{total}) and the air gap impedance (Z_{gap}) do not change at a given ultrasonic frequency as the amplitude of the electroadhesive voltage changes. Thus, the gap voltage (V_{gap}) is equal to

$$V_{gap} = \frac{Z_{gap}}{Z_{total}} V_{total} \quad (3)$$

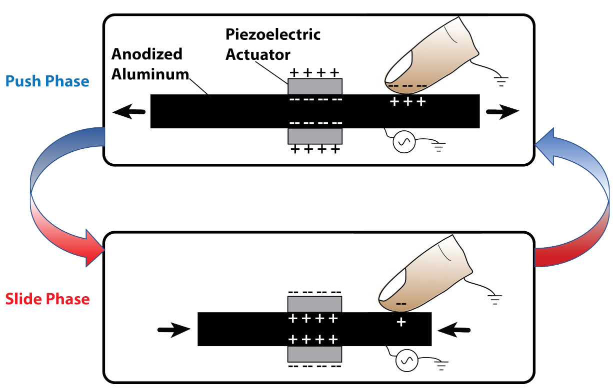


Fig. 4. Illustration of the lateral force generation in one period.

IV. Method and Experiments

Several experiments were performed to determine the relationship between lateral force and lateral velocity (v_l), the total electroadhesive voltage (V_{total}), and the phase difference (θ) between lateral velocity and electroadhesive voltage.

A. Experiment Setup

As shown in figure 5, the UltraShiver was mounted to mechanical ground with six brass flexures. A six-axis force sensor (ATI17 Nano load cell), which was placed underneath the UltraShiver, was used to measure lateral and normal forces. A Laser Doppler Vibrometer (LDV) was used to measure the lateral velocity at the end of the surface. The piezoelectric actuators were controlled with a piezoelectric amplifier outputting a sinusoidal signal at 30.1 kHz, and the electroadhesive voltage was modulated with a high voltage source (TREK 610C). Because the electroadhesion effect varies roughly as the square of the voltage, a DC offset was introduced to avoid frequency doubling. More details of the parameters are reported in each experiment.

During the experiments, the electrically grounded finger lightly touched the surface while pressing against an acrylic block to mechanically ground the rest of the finger (see figure 5). The interface area between the fingertip and the surface was close to the short edge of the surface, in order to acquire a high relative lateral velocity (shown in the section V-A). All the signals were generated and recorded using an NI USB-6361 with a 200 kHz sampling frequency.

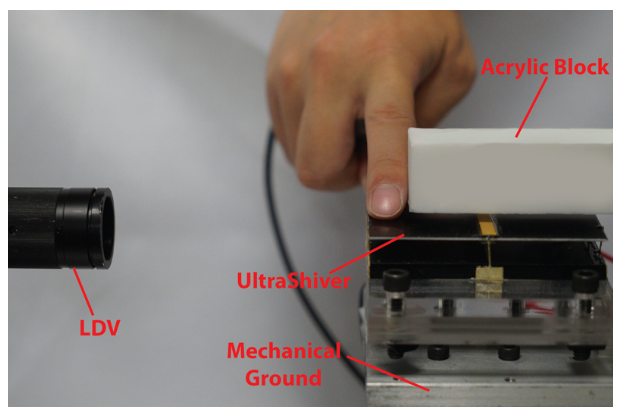


Fig. 5. Experiments platform.

B. Experiment 1: Effect of Phase

This experiment was used to investigate the effect of the phase between the lateral velocity and the electroadhesive voltage. The voltage of piezoelectric actuators was set to 100 V peak-to-peak at 30.1 kHz. The electroadhesive voltage was set to a sinusoidal voltage of amplitude 120 V and with an offset of 200 V. The frequency of the electroadhesive voltage (30.09 kHz) was set to 10 Hz less than that of the piezoelectric voltage, so that the phase between the lateral velocity and the electroadhesive voltage varied at 10 Hz. The experimental duration was 0.5 seconds.

C. Experiment 2: Effect of Lateral Velocity and Pressing Force

Even though the normal force was measured by the force sensor, the experimenter kept a constant pressing force (0.266 $\pm$ 0.027 N) as effectively as possible. The parameters of the electroadhesive voltage were the same as those in experiment 1. The voltage of piezoelectric actuators was randomly chosen from 4 V to 120 V peak-to-peak. Each measurement was repeated five times. The experimental duration for each trial was 1 second.

In addition, the experimenter repeated this experiment using a stronger pressing force (0.620 $\pm$ 0.041 N), in order to analyze the effect of different pressing forces on the lateral force.

D. Experiment 3: Effect of Electroadhesive Voltage

Since the electroadhesive voltage contains AC and DC components, the electroadhesive force (F_e) is represented as (together with equation 3):

$$F_e \propto \left(\frac{Z_{gap}(f)}{Z_{total}(f)} V_{AC} \operatorname{Sin}(2\pi f t) + \frac{Z_{gap}(0)}{Z_{total}(0)} V_{DC}\right)^2 \quad (4)$$

where f, V_{AC} and V_{DC} represent the frequency, the AC component magnitude, and the DC component of total voltage (V_{total}), respectively. In this experiment, the piezoelectric voltage was fixed at 100 V peak-to-peak, which was chosen in the saturation range of the lateral velocity (more details are given in sections VI-C and VI-D). The amplitude of the AC voltage (V_{AC}) varied from 20 V to 150 V under three different DC voltages (V_{DC}), including 100 V, 150 V, and 200 V. All the combinations of V_{AC} and V_{DC} were randomly chosen. Each combination was repeated five times. The experimental duration for each trial was 1 second.

E. Experiment 4: Effect of the Ratio of AC to DC Voltage

In this experiment, we defined a variable η, the ratio of AC to DC voltage, as

$$\eta = \frac{V_{AC}}{V_{DC}} \quad (5)$$

This experiment investigated the effect of this ratio η on the lateral force under the same peak electroadhesive voltage.

$$V_{AC} + V_{DC} = 240 \text{ V} \quad (6)$$

η was randomly chosen from 0.1 to 1.6 and measurements for each value were repeated five times. During each trial, the piezoelectric voltage was fixed at 100 V peak-to-peak, which was chosen in the saturation range of the lateral velocity (more details are given in sections VI-C and VI-D). The experimental duration for each trial was 1 second.

V. Results

A. Vibration Velocity Profile

Figure 6 shows the lateral and normal velocity on the left side of the surface. There is a large lateral velocity (1100 mm/s) at the edge of the surface. The lateral velocity decreases to 300 mm/s at the farthest-right measurement point, which is 8.25 mm from the center of the surface. There is only one longitudinal nodal line in the center, which matches the results of finite element analysis in figure 2. In addition, there is a normal oscillation with five nodal lines. The amplitude of the normal velocity is around 80 mm/s, which is 7% of the amplitude of the lateral velocity.

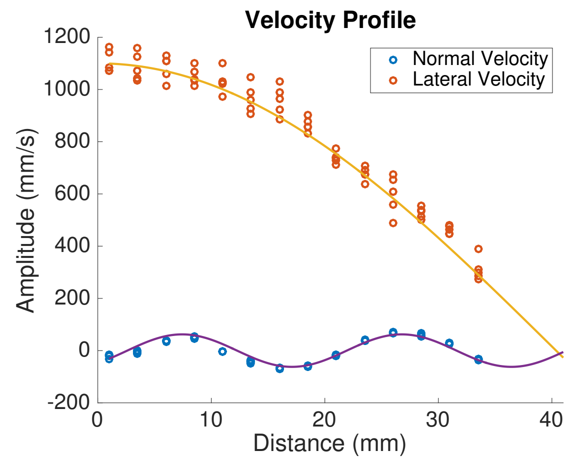


Fig. 6. Vibration velocity profile of the UltraShiver. The x axis represents the distance from a measurement point to the left short edge.

B. Effect of Phase

Figure 7 shows the relation between the lateral force and the relative phase (i.e., the phase between lateral velocity and electroadhesive voltage). The maximum lateral force is achieved when the relative phase is equal to 45 or 225 degrees. This means that the lateral velocity is optimally chosen to lead the electroadhesive voltage 45 or 225 degrees.

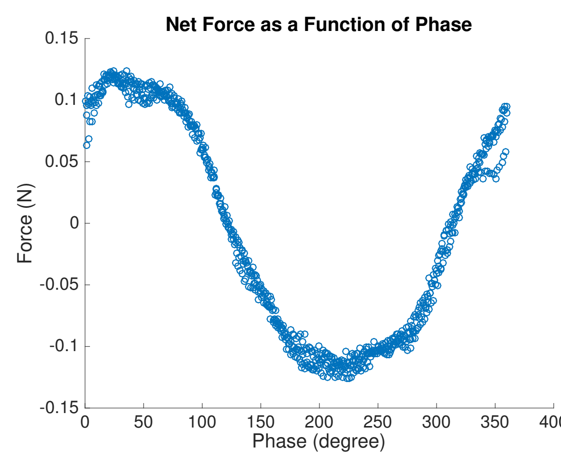


Fig. 7. Lateral force as a function of phase between the lateral velocity and the electroadhesive voltage.

C. Effect of Lateral Velocity and Pressing Force

Figure 8 shows the relation between the lateral velocity and the lateral force under two different pressing forces. The lateral velocity changes from 100 mm/s to 1000 mm/s. The range of the lateral force varies from 0 to 0.35 N. In the case of low normal force, there are two turning points: when the lateral velocity is around 300 mm/s, and when it is around 700 mm/s. Before the lateral velocity reaches 300 mm/s, the UltraShiver cannot generate a net lateral force. When the lateral velocity increases from 300 mm/s to 700 mm/s, the lateral force increases significantly from 0.1 N to 0.35 N. When the lateral velocity increases from 700 mm/s to 1000 mm/s, the lateral force remains almost constant at 0.35 N.

As the pressing force increases, there is a similar velocity-force relation as that under a low force. There are still two turning points, but they shift slightly to around 400 mm/s and 820 mm/s. When the lateral velocity is in the range of 300 mm/s to 820 mm/s, the lateral force with a high pressing force is less than that with a low pressing force.

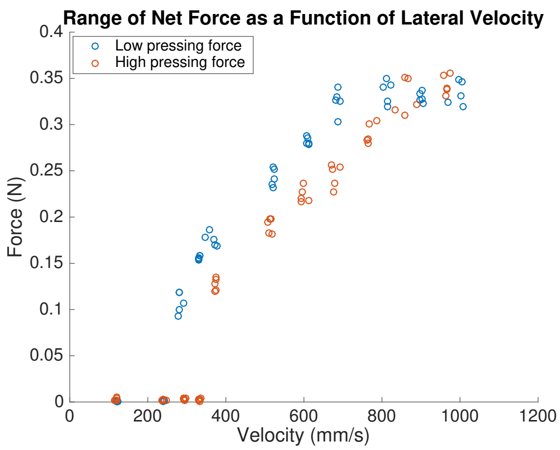


Fig. 8. Lateral force as a function of the lateral velocity under different pressing forces.

D. Effect of Electroadhesive Voltage

Figure 9 presents the relation between the amplitude of the AC voltage and the lateral force under different DC voltages. The maximum lateral force is around 0.4 N when the AC voltage (V_{AC}) is 140 V and the DC voltage (V_{DC}) is 200 V. Generally, the lateral force increases as a function of both AC voltage and DC voltage.

E. Effect of the Ratio of AC to DC Voltage

Figure 10 shows the variation of lateral force with the ratio η. Notably, there is a peak in lateral force when η is about 0.55.

VI. Discussions

A. Vibration Velocity Profile

Even though the UltraShiver is intended to generate longitudinal motion only, the velocity profile data show that there is still a small amount of normal motion. This may be due to imperfections in the fabrication of the UltraShiver: the relative position of the piezoelectric actuators on the anodized aluminum is manually adjusted, and the actuators may not be placed exactly symmetrically. Alternatively, the electrical and mechanical properties of the two actuators may

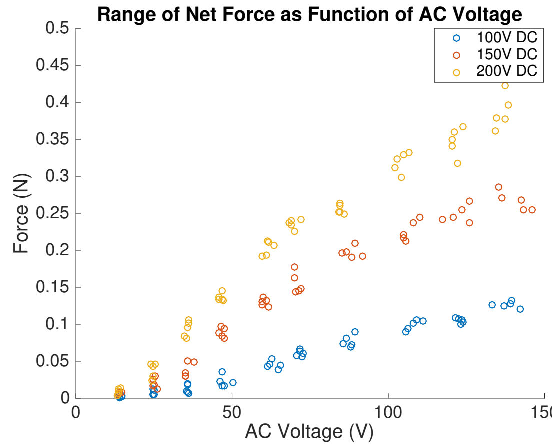


Fig. 9. Lateral force as a function of the AC component of the electroadhesive voltage under different DC components.

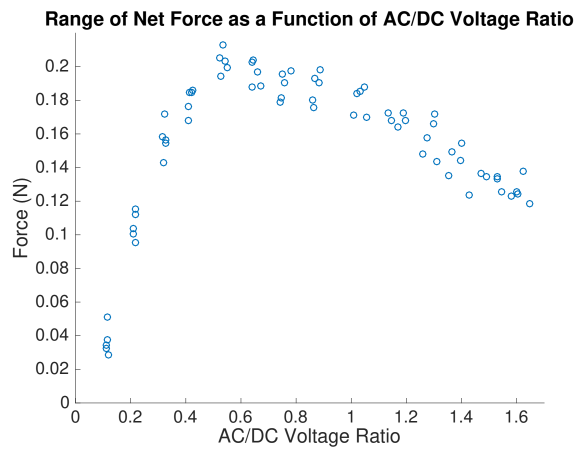


Fig. 10. Lateral force as a function of ratio of AC to DC voltage magnitudes.

not be exactly the same. Either reason would lead to non-zero normal motion. Fortunately, the normal motion is weak compared to the lateral motion. The rest of experiments also suggest that the normal motion does not affect the lateral force generation or the control of its direction.

B. Effect of Phase

In equations 1, 2 and 4, there is a maximum lateral force when the lateral reaction force (F_l) and the friction force (F_{push} or F_{slide}) are in-phase or anti-phase. However, the mechanical impedance and the electrical impedance may affect the optimal phase between the lateral velocity and the electroadhesive voltage. An in-depth explanation of the results (45 or 225 degrees) should derive from measurements of the mechanical and electrical impedance, which are beyond the scope of this paper.

C. Effect of Lateral Velocity and Pressing Force

The relation between the lateral velocity and the lateral force can be divided into three zones, including the stuck zone, the linear zone, and the saturation zone.

In the stuck zone, the reaction force (F_l) from the relative lateral velocity (v_l) is less than the low friction force (F_{slide}). The fingertip is always stuck during the back-forth motion of the surface. Thus, the UltraShiver cannot generate the lateral force.

In the linear zone, the reaction force (F_l) is less than the high friction force (F_{push}) and larger than the low friction force (F_{slide}). The fingertip will slide in one direction and get stuck in another direction. According to equation 1, there is a linear relation between the lateral velocity and the lateral force for a given electroadhesive voltage.

In the saturation zone, the reaction force (F_l) is larger than the high friction force (F_{push}). The fingertip slides in both directions. Based on equation 2, the lateral force is close to constant in this zone for a given electroadhesion voltage. Thus, this zone presents a saturating relation between the lateral velocity and lateral force.

In addition, as we increase the pressing force, the friction force from the pressing force increases. Even though there are still the three zones, the UltraShiver needs more lateral velocity to overcome the increasing friction force. Thus, the lateral velocity of the two turning points will shift to higher values.

D. Effect of Electroadhesive Voltage

When testing the effect of electroadhesion voltage, the lateral velocity was set to a high value of about 1000 mm/s. This ensured that the lateral force stayed in the saturation zone (sliding in both directions). In saturation, we would expect an increase in either AC or DC voltage to increase lateral force (see equations 2 and 4). The data show precisely this for the selected electroadhesive voltage range.

E. Effect of the Ratio of AC to DC Voltage

This experiment was also performed at a lateral velocity of about 1000 mm/s ensuring operation in the saturation zone. Two factors motivated our interest in the optimal ratio of AC to DC voltage. First, the electroadhesion force varies, roughly speaking, as the square of the gap voltage. Because of the square law dependence, it is necessary to minimize the absolute value of the gap voltage during the sliding phase. To accomplish this the zero-mean AC component is offset by a DC component. The second consideration is that the transfer function relating applied voltage to gap voltage is frequency dependent, which means that the AC and DC components of the gap voltage will not be identical to those of the applied waveform. Thus, it is not sufficient merely to select equal DC and AC magnitudes (η = 1). Indeed, as the data show, peak force occurs near η = 0.55, suggesting that DC gap voltage is attenuated more than AC gap voltage. This may be due to "leakage" through the stratum corneum [20].

VII. Conclusions

The UltraShiver, which can generate a strong lateral force (400 mN) under a silent operation (around 30 kHz), is a simple and robust device that should serve as the basis for a wide variety of bare finger force feedback applications. Force feedback, however, requires integration with finger position sensing, which is a part of our ongoing work.

Acknowledgment

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